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Development of Solar Powered Multifaceted Agricultural Pesticide Spraying Machine

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Abstract- Agricultural pesticide spraying is an essential crop-protection operation, but conventional hand-operated, engine-driven and battery-dependent sprayers can impose operator effort, fuel dependence, inconsistent application and chemical loss. The 21 studies reviewed in this paper collectively cover photovoltaic sprayers, multi-nozzle systems, remote and robotic platforms, autonomous aerial spraying, air-assisted atomization, spray-drift management, variable-rate application and machine-vision control. The literature indicates a progression from replacing manual or fossil-fuel power with photovoltaic electric pumping toward systems that also adapt spray delivery to crop geometry and target conditions. Solar-powered trolley and knapsack systems demonstrate the feasibility of photovoltaic operation and reductions in operator burden; remote and robotic systems provide greater separation between the operator and spray plume; and precision systems demonstrate substantial reductions in applied chemical when spray rate is matched to the target. At the same time, solar intermittency, battery capacity, machine mass, nozzle calibration, pressure control, spray uniformity, drift and sensing cost remain important limitations. This review synthesizes the 21 studies through a transparent corpus-based review methodology and identifies design principles relevant to a practical solar-powered multifaceted sprayer. Based on the synthesis, a modular machine architecture is proposed in which solar PV, battery storage, an efficient DC pump, pressure regulation, a filtered multi-nozzle boom and a stable wheeled chassis form the basic platform, while remote control, flow/pressure sensing and machine vision can be added progressively. The review concludes that the most practical development pathway is a layered system that combines renewable energy, mechanical simplicity, adjustable spraying and provision for future precision automation.

Keywords- Solar-powered sprayer, agricultural pesticide spraying, photovoltaic energy, multi-nozzle system, precision agriculture, spray drift, agricultural robot, sustainable farming.

I. INTRODUCTION

Agricultural productivity depends on timely management of weeds, insects and diseases. Chemical spraying remains an important crop-protection operation because the method can deliver a treatment rapidly over a large area. However, the effectiveness of spraying depends on more than the presence of a pump. Nozzle type, pressure, target distance, droplet size, travel speed, canopy geometry and atmospheric conditions influence deposition and off-target loss. The supplied literature shows that agricultural spraying is therefore moving from simple manual equipment toward electrically powered, solar-powered, remotely operated and sensor-assisted platforms.

Conventional knapsack sprayers are attractive because of their simplicity and low initial cost, but the operator must carry the liquid load and maintain pumping effort. Engine-driven systems provide higher pressure and field capacity but introduce fuel consumption, noise, vibration and maintenance. Solar-powered electric pumping offers an alternative in locations where grid power is limited. Swami et al. demonstrated a 100 Wp photovoltaic trolley sprayer with a 50 L tank, while Sinha et al. developed a 60 Wp solar knapsack system with a 14 L tank and reported lower physiological demand than the comparison systems [6], [9].

The literature also shows that renewable power alone does not solve the problem of application quality. Singh et al. demonstrated that nozzle selection, pressure and boom position influence swath width and droplet characteristics [3]. The precision-spraying studies then extend this principle by using crop information to change spray rate or airflow. Xun et al.

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reported a 43% reduction in applied pesticide volume for a precision orchard system, while Luo et al. reported a 59.73% reduction in spray volume compared with continuous spraying [15], [20].

Figure 1. Evolution of agricultural pesticide spraying technology.

The term multifaceted in this review describes a machine that addresses several connected requirements rather than optimizing only one parameter. The desired platform should provide renewable energy, reliable pumping, adjustable application, practical mobility and reduced operator exposure. It should also allow future integration of sensors and automation. This approach is supported by the literature because the individual technologies already exist, but they are often reported as separate prototypes. Solar sprayers emphasize energy independence, robotic systems emphasize mobility and safety, nozzle studies emphasize droplet behavior, and precision systems emphasize sensing and variable-rate control.

The environmental dimension is equally important. Spray drift can cause deposition outside the intended target, while excessive application increases chemical use and cost. Khan et al. identify nozzle characteristics, droplet size, operating pressure, travel speed, liquid properties and atmospheric conditions as major factors affecting spray drift [19]. Byers et al. similarly showed that aerial spray deposition and uniformity vary with operational parameters such as nozzle type, height and speed [17]. These findings indicate that a future machine should treat spray quality as a system-level performance measure rather than simply reporting pump discharge.

The recent studies also demonstrate a trend toward feedback control. Mu et al. combined a UGV, stereo vision, RTK positioning and targeted actuation for apple blossom thinning and reported 93.8% flower-cluster detection precision and a substantial reduction in chemical use compared with conventional air-blast spraying [11]. İtmeç and Bayat used laser sensing to adapt airflow and liquid flow to canopy conditions and reported spray-liquid savings across several orchard crops [18]. These results suggest that sensing can produce significant gains, but they also increase cost, calibration requirements and computational complexity.

For a mechanically oriented and cost-conscious agricultural machine, a complete autonomous system is not necessarily the first development step. A more practical pathway is to establish a robust solar-powered platform with adjustable pressure and multi-nozzle coverage, then add remote control and sensing as modular upgrades. The review therefore focuses on the technical evidence needed to define that base platform and the interfaces required for later precision functionality.

Objectives

- To review the development and performance of solar-powered agricultural pesticide sprayers.
- To compare knapsack, trolley, multi-nozzle, robotic, UAV and precision-spraying approaches.
- To identify the effects of pressure, nozzle selection, droplet characteristics, speed and spray height on application.

Scope

This paper is a corpus-based engineering literature review of the 21 research papers supplied for the project. All 21 papers were retained because each contributes to at least one of the themes required for the proposed machine: solar energy, spraying mechanics, nozzles and atomization, robotic mobility, remote control, precision sensing, variable-rate application, UAV spraying or spray-drift management. The review is narrative and comparative rather than a statistical meta-analysis; performance figures are reported only as findings of the cited studies and are not presented as results of the proposed machine.

II. REVIEW METHODOLOGY

The review methodology was designed to make the use of the 21-paper corpus explicit. The starting corpus consisted of the 21 research papers supplied for this project. Each paper was examined for its objective, machine or spraying configuration, power source, control method, nozzle or atomization approach, operating parameters, reported performance and limitations. The studies were then grouped into thematic categories so that papers using different technologies could be compared on common engineering requirements.

The inclusion rule was direct relevance to agricultural spraying or to a technology that can materially influence a solar-powered multifaceted spraying machine. Papers were retained when they addressed one or more of the following: photovoltaic energy supply, agricultural spray equipment, multi-nozzle or boom design, pump and pressure behavior, robotic or remote spraying, machine vision, variable-rate application, aerial spraying, air-assisted atomization or spray-drift reduction. Papers were not excluded merely because they used a different crop or platform; instead, crop- and platform-specific results were interpreted as evidence for a broader design principle. For each study, the review extracted five categories of information: (1) system architecture, (2) energy and actuation arrangement, (3) spraying and sensing technology, (4) measured performance, and (5) limitations or unresolved issues. The comparison was then synthesized around the engineering questions most relevant to the proposed machine: How should power be supplied and stored? How should spray flow and pressure be regulated? How should a multi-nozzle boom be arranged? How can operator exposure be reduced? Which sensing technologies offer useful future upgrades? What trade-offs occur between precision and system cost?

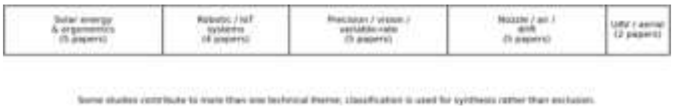

Figure 2. Thematic classification of the 21 reviewed studies.

The classification is not mutually exclusive. For example, a solar-powered robot may also be a multi-nozzle system, and a precision orchard sprayer may use both machine vision and variable-rate flow control. The purpose of the classification is therefore to expose the technological relationships rather than to force each paper into one category.

Review Synthesis Framework

Engineering theme	Evidence extracted from the literature	Design implication
Energy	PV rating, battery capacity, pump power, operating continuity	Size PV and storage from measured duty cycle; protect battery
Spraying	Pressure, nozzle type, discharge, target distance, droplet behavior	Use regulator, filter and interchangeable nozzles
Mobility	Knapsack, trolley, UGV and remote vehicle arrangements	Prefer stable wheeled chassis for reduced carrying load
Safety	Ergonomics and remote operation	Separate operator from chemical load and spray plume
Precision	Vision, laser, ultrasonic, GPS/RTK and variable-rate control	Provide modular sensor/controller interfaces
Environment	Drift, deposition, chemical saving and airflow	Evaluate coverage and drift, not only pump output

III. LITERATURE REVIEW: SOLAR-POWERED AND ERGONOMIC SYSTEMS

Swami et al. developed a trolley-based solar PV sprayer using a 100 Wp polycrystalline PV array, a 12 V, 32 Ah battery and a 60 W DC pump. The system used a 50 L tank and could operate from direct solar power or stored battery energy. The reported field work indicated satisfactory operation for agricultural spraying and identified the period from approximately 9:00 AM to 3:00 PM as favorable under the study conditions [6]. The study establishes that photovoltaic pumping can support a relatively high-capacity mobile sprayer, but the dependence on available solar energy must be managed through storage.

Sinha et al. developed a solar-powered knapsack sprayer with a 14 L tank, 60 Wp solar module and electric pumping arrangement. The system included protection against deep discharge and overcharging and an anti-clogging filter. The study reported lower physiological demand and discomfort compared with manual and air-assisted comparison systems, together with useful field coverage [9]. The principal contribution is therefore ergonomic as well as energetic: replacing manual pumping can stabilize the spraying process while reducing repetitive effort.

Pawar et al. reviewed solar-powered agricultural sprayers and identified portable, trolley and high-clearance configurations. The review highlights a recurring system architecture consisting of solar panel, charge controller, battery, DC pump, tank, boom and nozzles. It also points toward multi-purpose solar carts that can be used for more than spraying, improving the utilization of the energy system [8]. This observation supports the present concept of a multifaceted platform rather than a single-purpose sprayer.

Ahmmed et al. reported a compact solar-powered backpack sprayer using a photovoltaic module, battery and electric pump. The study is relevant because it shows that even a small solar system can provide stable discharge under field conditions, while also illustrating the trade-off between portability and application capacity [7]. A compact backpack design reduces chassis mass but continues to place the liquid load on the operator.

Manab et al. developed a solar-powered sprayer for remote oil-palm plantations using a 50 Wp monocrystalline panel, two 12 V/24 Ah VRLA batteries, a variable-pressure DC pump and an automatic transfer switch. Their field test reduced reported spraying time from eight hours manually to two hours, with a maximum pressure of 70 psi and a reach of 3.5 m [21]. The dual-battery arrangement is particularly relevant to the proposed machine because it addresses continuity when sunlight or primary-battery availability changes.

Table I. Solar-powered and ergonomic studies

Ref.	Configuration	Key reported contribution	Implication
[6]	100 Wp PV; 32 Ah battery; 60 W pump; 50 L trolley	Direct/battery operation; satisfactory field spraying	Use storage to reduce solar intermittency
[7]	Compact PV backpack system	Stable discharge under field operation	Portability trades against field capacity
[8]	Review of PV agricultural sprayers	Common PV–battery–pump–boom architecture	Supports modular/multi-purpose platform
[9]	60 Wp PV; 14 L knapsack	Lower physiological demand; useful field coverage	Electric pumping improves ergonomics
[21]	50 Wp PV; dual 24 Ah batteries; ATS	75% reduction in reported spraying time; 70 psi; 3.5 m reach	Battery switching improves continuity

III. LITERATURE REVIEW: MULTI-NOZZLE, ROBOTIC AND REMOTE SYSTEMS

Singh et al. evaluated a multi-nozzle backpack power sprayer for cotton and examined nozzle performance under different pressures and target distances. The study showed that swath width and droplet characteristics changed with pressure and boom position [3]. The result is directly relevant to a multifaceted machine: a multi-nozzle boom should not be treated as a fixed collection of outlets. Nozzle type, spacing, height and pressure must be selected together to obtain uniform coverage.

Londhe and Sujata developed a remotely operated pesticide sprayer robot that combined a mobile platform, camera-based image processing and localized spray actuation. The pump could be activated when a diseased region was identified, rather than operating continuously [1]. Although the system was not designed around solar power, its target-selective concept is important because it demonstrates how sensing can be coupled directly to spray actuation.

Narendra Babu et al. developed an IoT-oriented pesticide spraying robot using an ARM7 controller and Bluetooth communication. The reported prototype emphasized low-cost remote operation, a limited liquid load and reduced direct operator involvement [4]. Owoeye et al. developed a solar-powered herbicide spraying robot using an ESP32, Bluetooth, battery supply, DC motors and a pump. The system used three nozzles and was tested over different ground surfaces [13]. Together, these studies show that wireless control and multi-nozzle spraying can be implemented with relatively accessible electronics.

Kayode et al. developed a remote-controlled solar-powered pesticide spraying vehicle with photovoltaic charging, a large-capacity battery, drive motor, high-pressure pump and a 20 L tank. The reported system demonstrated remote spraying over a substantial distance and showed that ground mobility can separate the operator from the spray plume [10]. The main trade-off is vehicle mass: the larger battery, solar modules, tank and drive system improve capability but increase mechanical and energy requirements.

Anuradha et al. presented a solar-powered automatic pesticide-related agricultural control system using PLC, RF communication and sensors [2]. While the work is broader than a mobile sprayer, it contributes a useful control principle: agricultural equipment can combine sensing, programmed logic and actuation instead of relying entirely on manual operation.

Table II. Robotic, remote and control-oriented studies

Ref.	Technology	Main contribution	Limitation relevant to integration
[1]	Camera + PIC + remote robot	Localized disease-based spray actuation	Prototype complexity; not solarbased
[2]	PLC + RF + agricultural sensors	Automatic control and pesticide-related process management	Not a complete mobile sprayer
[4]	ARM7 + Bluetooth robot	Low-cost remote spraying approach	Limited payload/control sophistication
[10]	Remote solar ground vehicle	Operator separation; 20 L tank; high-pressure pumping	Greater mass and energy demand
[13]	Solar + ESP32 + mobile application	Three-nozzle mobile herbicide platform	Remote control rather than autonomous perception

Critical Synthesis

The robotic literature suggests that remote operation should be considered a safety and usability feature rather than an end in itself. For the proposed machine, a manual mode should remain available for simple operation, while remote control can be added to reduce exposure. The chassis and electrical system should therefore be designed with a controller, emergency stop and protected wiring from the beginning, even if full autonomy is not implemented in the first prototype.

IV. PRECISION, VISION, UAV AND AIR-ASSISTED SPRAYING

Dai et al. developed a vision-based autonomous aerial spray system using an octocopter, a spray device, machine vision, task scheduling and target localization [12]. The work demonstrates the potential of visual perception for autonomous agricultural spraying, but aerial platforms introduce additional variables such as rotor downwash, flight speed, spray height and weather sensitivity. For a ground-based solar machine, the main transferable lesson is the use of sensing to determine when and where spraying should occur.

Mu et al. combined a UGV with stereo vision, RTK positioning and a solenoid-controlled spray end-effector for apple blossom thinning. Their system detected flower clusters and achieved 93.8% detection precision in the reported experiments. The chemical requirement was lower than the conventional air-blast comparison, and the system was faster than an earlier cartesian target sprayer [11]. This demonstrates the potential of targeted actuation on a ground vehicle.

Xun et al. evaluated advanced orchard spraying systems and used tree-row volume to adapt application rate. The precision system reduced applied pesticide volume by 43% relative to conventional spraying. The study also reported reductions in ground and airborne drift under the tested conditions [15]. The important general principle is that application rate should be linked to crop volume or target characteristics rather than maintained as a constant value.

İtmeç and Bayat developed a real-time variable-rate air and liquid sprayer using six laser sensors and a hydraulic turbofan. Their experiments reported spray-liquid savings of 58.55% for grapefruit, 69.90% for pecan and 68.01% for persimmon, with corresponding fuel savings [18]. The study demonstrates that adapting both liquid flow and airflow can reduce inputs, although such a system requires additional sensing and calibration.

Luo et al. developed a machine-vision precision spraying control system using canopy segmentation, spray-volume calculation and an extended-state-observer fuzzy controller. The reported system reduced spray volume by 59.73% compared with continuous spraying and achieved strong canopy coverage and deposition performance under the tested conditions [20]. The study supports the use of feedback rather than uncontrolled maximum pressure.

Wandkar et al. developed an air-assisted sleeve-boom sprayer for greenhouse floriculture and reported improved penetration and uniformity at an optimized combination of airflow and liquid discharge [14]. Ou et al. designed an air-assisted nozzle using transverse air flow to atomize liquid and investigated its droplet and deposition behavior [16]. These studies show that air assistance can improve atomization and penetration, but it also introduces additional power demand and mechanical complexity.

V. SPRAY DRIFT AND APPLICATION QUALITY

Khan et al. reviewed spray-drift reduction technologies and identified droplet size, nozzle design, pressure, travel speed, liquid properties and atmospheric conditions as important variables [19]. Byers et al. likewise showed that aerial spray deposition and uniformity depend strongly on operating parameters [17]. Therefore, the proposed machine should be evaluated by spray coverage, application rate, deposition uniformity and drift risk in addition to pump pressure and tank capacity.

V. AGRICULTURAL PESTICIDE SPRAYING TECHNIQUES

1. Manual and Knapsack Spraying

Manual knapsack sprayers are mechanically simple and remain suitable for small holdings, but the operator carries the tank and maintains pumping effort. Solar-powered knapsack systems replace manual pumping with an electric pump and can reduce physiological load [9]. Their limitation is that the liquid mass remains on the operator. The proposed wheeled machine addresses this limitation by transferring the tank and energy system to the chassis.

2. Multi-Nozzle and Boom Spraying

Multi-nozzle systems increase effective swath and can reduce the number of passes. However, pressure and nozzle spacing must be selected to obtain suitable overlap and uniformity. Singh et al. showed that spray characteristics change with pressure, target distance and boom orientation [3]. The proposed boom should therefore permit nozzle replacement, height adjustment and pressure regulation.

3. Air-Assisted Spraying

Air-assisted systems can improve canopy penetration by using airflow to transport and atomize droplets [14], [16]. Their disadvantages are added blower power, mass and control complexity. A low-cost solar machine should treat air assistance as an optional module rather than an essential component unless field trials demonstrate a clear benefit.

4. Ground Robotic Spraying

Ground robots can carry the tank and pump while reducing operator exposure. The literature demonstrates remote control using microcontrollers and wireless communication [1], [4], [10], [13]. Mechanical design must nevertheless address traction, stability, turning radius, ground clearance and energy use. A manually steerable wheeled chassis is a practical first stage, with remote drive as a later upgrade.

5. Unmanned Aerial Spraying

UAVs can access crops without ground contact, but their spray deposition is affected by rotor downwash, flight height, speed and atmospheric conditions [12], [17]. UAV technology is therefore not directly adopted in the proposed ground machine; instead, the review transfers its most relevant concept—sensor-based targeting—to the future controller.

6. Precision and Variable-Rate Spraying

Precision spraying uses crop information to modify liquid flow, pressure or airflow. The reported reductions in chemical use by Mu et al., Xun et al., İtmeç and Bayat, and Luo et al. indicate that target-aware application can be substantially more efficient than continuous spraying [11], [15], [18], [20]. The challenge is cost and calibration. A modular architecture allows these functions to be added after the basic mechanical system is validated.

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VI. CRITICAL COMPARATIVE ANALYSIS

Feature	Conventional/manual	Solar/assisted	Robotic/precision	Implication for proposed machine
Energy	Human/fuel	PV + battery	PV/battery + electronics	Use PV charging with battery storage
Spray control	Mostly manual	Electric pump	Feedback/variable rate	Adjustable pressure; future flow feedback
Coverage	Operator dependent	Boom/nozzles	Targeted/variable	Multi-nozzle adjustable boom
Mobility	Operator carries load	Trolley/backpack	UGV/UAV	Stable wheeled chassis
Safety	High operator proximity	Lower effort	Remote/targeted	Manual + remote modes
Precision	Low	Moderate	High	Provide sensor/vision interfaces
Cost	Low initial	Moderate	Higher	Layered modular development

VII. PROPOSED MULTIFACETED SOLAR-POWERED SPRAYER ARCHITECTURE

The literature supports a layered machine architecture in which the basic functions are mechanically and electrically independent enough to allow future upgrades. The proposed platform is not presented as an experimentally validated machine; it is a design direction derived from the reviewed evidence. Its primary objective is to combine the most transferable features of the 21 studies without assuming that every advanced technology is necessary for the first prototype.

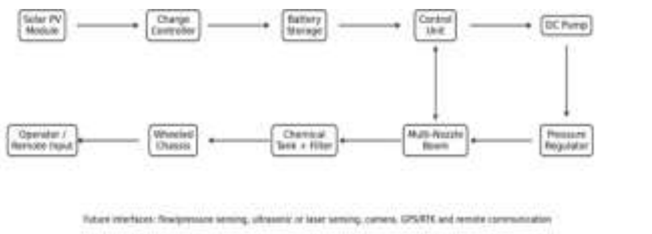

Figure 3. Proposed modular architecture for the multifaceted solar-powered sprayer.

1. Solar Energy Subsystem

A photovoltaic module supplies electrical energy to a charge controller and rechargeable battery. The PV rating should be selected from the measured pump and drive load, desired operating duration and expected solar availability rather than copied from another prototype. The literature includes systems using 15 W to 100 Wp-class PV arrangements and both single- and dual-battery configurations [6], [7], [9], [21].

2. Pump and Pressure Subsystem

The pump should provide the pressure and discharge required by the selected nozzle set. A pressure regulator and gauge are recommended because maximum pump pressure is not necessarily the optimum spraying pressure. A filter before the pump and cleanable nozzle tips are also important for preventing blockage. The pressure system should include electrical overload and dry-run protection where appropriate.

3. Multi-Nozzle Boom

The boom should carry replaceable nozzles at controlled spacing and allow height adjustment. The number of nozzles should be selected from the desired swath and pump capacity. The boom should be rigid enough to maintain nozzle alignment while remaining removable for maintenance. The literature indicates that pressure, distance and nozzle arrangement affect spray pattern, so the design should support calibration rather than assuming one fixed setting [3].

4. Chassis and Mobility

A wheeled chassis transfers the tank, battery and pump mass away from the operator. The frame should maintain a low center of gravity, sufficient ground clearance and stable wheel contact. A modular tank support allows capacity changes. The solar panel should be mounted securely and, where practical, allow angle adjustment.

5. Control and Safety

The basic control panel should include pump start/stop, pressure indication and battery status. An emergency stop, protected electrical wiring, chemical-resistant hoses and secure tank mounting should be provided. A future remote-control module can operate the pump and vehicle while preserving manual override.

6. Future Sensor Layer

Flow and pressure sensors can provide closed-loop spray control. Ultrasonic or laser sensing can estimate canopy or obstacle distance, while a camera can support crop-row or disease-target detection. GPS or RTK can support navigation. These additions should be modular because the reviewed precision systems show both substantial benefits and higher implementation complexity [11], [18], [20].

VIII. COMPARATIVE ANALYSIS OF THE 21 REVIEWED STUDIES

The following table consolidates the complete 21-paper corpus. The purpose is not to rank the studies because their objectives and platforms differ, but to identify which contribution can be transferred to the proposed machine and what limitation remains.

Ref.	Study / year	System and key technology	Main reported contribution	Transferable lesson / limitation
[1]	Londhe & Sujata, 2017	Remote disease-targeting robot; camera + PIC	Localized spraying and remote operation	Target-based actuation; not solar
[2]	Anuradha et al., 2019	Solar agricultural control; PLC/RF/sensors	Automated process control and sensing	Useful control concept; broaderthan mobile spraying
[3]	Singh et al., 2019	Multi-nozzle backpack boom	Pressure/nozzle effects on swath and droplets	Need calibration of nozzle, pressure and position
[4]	Narendra Babu et al., 2023	IoT robot; ARM7/Bluetooth	Low-cost remote spraying	Remote safety; limited payload/control
[5]	Mulani, 2024	Survey of semi-automatic solar sprayers	Identifies PV, sensing, GPS and analytics needs	Calls for field-oriented integration
[6]	Swami et al., 2016	100 Wp PV; 32 Ah; 60 W pump; trolley	50 L mobile solar sprayer	Demonstrates PV pumping; sunlight dependence
[7]	Ahmmed et al., 2026	Compact solar backpack sprayer	Stable field discharge	Portable but lower capacity
[8]	Pawar et al., 2020	Review of solar agricultural sprayers	PV–battery–pump–boom architecture	Supports multi-purpose solar cart
[9]	Sinha et al., 2018	60 Wp PV; 14 L knapsack	Reduced physiological load	Improves ergonomics; liquid still carried
[10]	Kayode et al., 2024	Remote solar vehicle; high-pressure pump	Remote operation and 20 L tank	Good safety potential; high mass
[11]	Mu et al., 2025	UGV + vision + RTK + solenoid	93.8% detection precision; chemical saving	Strong precision; higher cost
[12]	Dai et al., 2017	Vision-based autonomous UAV	Target localization and autonomous spray	Transferable sensing; UAV-specific constraints
[13]	Owoeye et al., 2026	Solar + ESP32 + mobile app + 3 nozzles	Mobile-app-controlled solar robot	Useful modular electronics; remote not autonomous
[14]	Wandkar et al., 2015	Air-assisted sleeve boom	Improved penetration and uniformity	Additional blower power
[15]	Xun et al., 2023	Tree-row-volume precision spraying	43% applied-volume reduction	Strong evidence for variable rate

[16]	Ou et al., 2024	Transverse air-assisted nozzle	Air–liquid atomization and deposition study	Nozzle design can improve atomization
[17]	Byers et al., 2024	UAV spray deposition study	Uniformity depends on height/speed/nozzle	Parameter calibration is essential
[18]	İtmeç & Bayat, 2026	Laser-sensed air/liquid VRA	58.55–69.90% liquid savings reported	Precision benefit; calibration/cost
[19]	Khan et al., 2024	Spray-drift review	Identifies nozzle/pressure/droplet/environment effects	Drift must be evaluated explicitly
[20]	Luo et al., 2025	Machine vision + ESO-fuzzy control	59.73% spray-volume reduction reported	Feedback improves precision; computation needed
[21]	Manab et al., 2025	50 Wp PV + dual battery + ATS	75% reduction in reported spraying time	Continuity benefit; added mass/cost

VIII. PERFORMANCE PARAMETERS AND DESIGN CONSIDERATIONS

A review intended to guide machine development should translate published findings into measurable engineering parameters. The 21 studies collectively suggest that the proposed sprayer should be evaluated through four linked groups: energy performance, spraying performance, mobility and safety, and precision/environmental performance. Reporting only tank capacity or pump pressure would not be sufficient because a machine can produce high pressure while still delivering poor coverage or excessive drift.

1. Energy Performance

The photovoltaic subsystem should be evaluated by charging time, battery state of charge, pump electrical power, operating duration and energy consumed per unit field area. The solar panel should be selected with allowance for controller and charging losses rather than assuming that its rated peak power is continuously available. The studies by Swami et al., Sinha et al. and Manab et al. show different PV and battery combinations, illustrating that there is no single correct rating independent of tank size and pump duty [6], [9], [21].

For the proposed machine, the pump and vehicle drive should preferably be measured separately. This allows the design team to determine whether the spraying subsystem or traction subsystem dominates the energy demand. If the vehicle is manually pushed, the solar-battery system can be concentrated on spraying; if the machine is motor-driven, the battery must also support traction. This distinction can prevent an oversized battery and can help maintain a lower machine mass.

2. Hydraulic and Spray Performance

Hydraulic performance should include pump discharge, pressure stability, flow through each nozzle and total flow. Pressure should be measured at the pump outlet and, where possible, near the boom because hose losses can change the pressure available at the nozzles. A regulator should maintain a selected operating pressure while a relief path protects the system from over-pressure. The filter should be placed upstream of the pump or at an appropriate suction/discharge location based on the pump design.

The multi-nozzle boom should be calibrated by measuring the discharge of every nozzle over the intended pressure range. Nozzle-to-nozzle variation is important because a small difference in discharge can create visible bands of over- and under-application. The findings of Singh et al. reinforce the need to evaluate nozzle type, pressure and target distance together [3]. A practical acceptance criterion for the prototype should therefore be based on measured uniformity rather than on nominal nozzle specifications alone.

3. Field Capacity and Application Rate

Field capacity should be calculated from the effective treated width and travel speed while accounting for turning, refilling and interruptions. A wide boom can increase theoretical capacity, but if the machine becomes difficult to maneuver the effective capacity may not improve. The tank should therefore be sized with respect to field capacity and refill availability rather than simply maximizing volume.

Application rate should be expressed from measured total discharge and travel speed. For a uniform ground speed, a constant-pressure multi-nozzle boom can provide a repeatable application rate. If speed varies substantially, a future flow-control system can compensate. This is the point at which the precision literature becomes relevant: variable-rate systems show that the liquid flow can be adapted to target conditions, but the added sensors and controller must justify their cost [15], [18], [20].

4. Droplet, Coverage and Drift Considerations

Droplet behavior is a central link between pressure and agronomic performance. Smaller droplets may improve coverage under some conditions but can also increase susceptibility to drift. The literature therefore supports a selectable nozzle strategy rather than a single nozzle intended for every pesticide and crop. Air-assisted systems can alter atomization and penetration, but their additional power demand must be considered in a solar-powered platform [14], [16].

Coverage can be assessed using water-sensitive paper positioned at representative target locations. The resulting stain distribution can indicate whether the boom height, nozzle spacing and pressure are producing acceptable overlap. Drift should be assessed separately from target coverage because a system can produce high target deposition while also producing off-target loss. The review by Khan et al. emphasizes that pressure, droplet size, nozzle configuration and environmental conditions interact in determining drift [19].

5. Mechanical Stability and Human Factors

The frame should be designed around the combined mass of the liquid, battery, solar panel, pump and boom. The center of gravity should remain within the wheelbase during operation and turning. The boom should be supported so that vibration does not alter nozzle orientation. The handle or control interface should permit the operator to maintain a stable posture without standing directly in the spray path.

The ergonomic evidence from the solar knapsack study indicates that replacing manual pumping can reduce physiological load [9]. A wheeled platform can extend this benefit by transferring the tank load from the operator to the chassis. Remote operation can provide an additional safety layer, as demonstrated by the robotic studies [1], [4], [10], [13].

6. Reliability and Maintainability

Agricultural equipment operates in dusty, wet and chemically exposed environments. The proposed machine should therefore minimize inaccessible joints, use replaceable hoses and filters, protect electrical connections and provide a simple method for draining and cleaning the tank. The nozzle assembly should be removable without dismantling the complete boom. The solar panel support should resist vibration and accidental contact with crop foliage.

Reliability should be assessed by repeated operating cycles rather than a single demonstration. Useful measures include pump temperature, battery voltage, pressure stability, leakage, nozzle blockage frequency and mechanical fastener integrity. These measurements can reveal weaknesses that are not visible in a short field trial.

Table IV. Recommended validation metrics for the proposed machine

Parameter group	Recommended measurements	Purpose
Energy	PV power, battery voltage/current, charging time, operating time, energy/area	Verify solar-battery adequacy
Hydraulic	Pump flow, pressure stability, nozzle discharge, leakage	Verify reliable liquid delivery
Spray	Swath width, overlap, coverage, deposition uniformity	Verify application quality
Mobility	Travel speed, turning time, field capacity, stability	Verify practical field operation
Safety	Operator distance, emergency stop, leakage, electrical protection	Reduce exposure and failure risk
Environment	Drift indicators, droplet class, off-target deposition	Assess environmental performance

Economics	Energy cost, maintenance, refill time, operating cost/area	Assess practical adoption potential

These metrics provide a common basis for comparing the proposed machine with the published systems. They also prevent the evaluation from becoming dependent on one attractive performance number. A solar sprayer that operates for many hours but has poor coverage, high drift or excessive mass would not necessarily be a successful agricultural machine.

VIII-A. ECONOMIC AND SUSTAINABILITY PERSPECTIVE

The economic case for a solar-powered sprayer should include both capital cost and operating cost. PV panels, batteries, charge controllers and electric pumps increase the initial cost compared with a simple manual sprayer, but the solar energy source can reduce recurring fuel expenditure and can support operation where grid electricity is unavailable. The literature therefore suggests that the appropriate comparison is not only purchase price but total operating cost over the expected service period.

A multi-purpose energy system can improve utilization. Pawar et al. noted the possibility of using solar agricultural equipment for functions such as water pumping or lighting [8]. For the present machine, the battery and controller could similarly support auxiliary farm functions when spraying is not required, provided chemical safety and electrical isolation are maintained. This is a design opportunity rather than an experimentally established benefit and would require separate validation.

Sustainability also depends on reducing unnecessary chemical application. The reported reductions in applied volume in precision studies show that better targeting can complement renewable energy [11], [15], [18], [20]. Thus, the strongest sustainability pathway is not solar power alone; it is the combination of renewable energy, efficient actuation, accurate application and reduced off-target loss.

VIII-B. Limitations of the Reviewed Literature and Implementation Roadmap

The 21-paper corpus provides broad technical coverage, but direct numerical comparison between studies is limited because the experiments use different crops, field geometries, tank capacities, nozzle types, pressure ranges, travel speeds and evaluation methods. A percentage reduction reported for an orchard precision system should therefore not be interpreted as a guaranteed reduction for the proposed ground sprayer. The reported values are used as evidence of technical potential, while the proposed machine must be validated independently.

A second limitation is that several studies focus on a single subsystem. Solar-powered studies may emphasize energy and ergonomics without detailed spray-deposition analysis; nozzle studies may use laboratory conditions without complete vehicle integration; and precision studies may require crop-specific sensing and calibration. The proposed machine should therefore combine subsystem testing with whole-machine testing. This will help identify interactions that cannot be predicted by examining components separately.

A third limitation is environmental variability. Solar availability changes with time, cloud cover, panel orientation and shading. Field terrain changes traction and travel speed. Wind affects droplet transport and drift. Crop height and canopy density change the required spray configuration. These variables mean that a design that performs well under one set of conditions may require different settings elsewhere. A useful prototype should therefore provide adjustment rather than a single fixed operating point.

Implementation Roadmap

The first implementation stage should be a mechanical and hydraulic prototype. The frame, wheels, tank, pump, filter, pressure regulator and multi-nozzle boom should be fabricated and tested using clean water. The purpose of this stage is to establish structural stability, leakage control, pump performance, nozzle discharge and spray pattern before introducing chemical formulations.

The second stage should integrate the PV module, charge controller and battery. Charging behavior should be measured under representative sunlight conditions, while the battery should be monitored during continuous and intermittent pumping. The measured electrical load should be compared with the available solar input. This stage should also determine the operating time that can be achieved without excessive battery discharge.

The third stage should evaluate field performance. Tests should be conducted at several travel speeds and pressure settings, with different nozzle arrangements where applicable. Field capacity, application rate and coverage should be measured. Water-sensitive paper or a comparable method can be used to examine deposition. The results should be repeated sufficiently to identify variation between runs.

The fourth stage should introduce operator-safety and remote-control features. An emergency stop, protected wiring, secure battery mounting and leak-resistant fluid connections should be verified before remote operation. Remote driving should first be tested without pesticide and then under controlled spraying conditions. Manual override should remain available so that a communication failure does not leave the machine uncontrollable.

The fifth stage should evaluate precision features. A pressure sensor and flow sensor are the most direct additions because they measure variables already central to the spraying process. An ultrasonic or laser sensor can then be investigated for canopy or obstacle measurement. A camera and image-processing algorithm can be added only after the mechanical and hydraulic system is stable. This order follows the evidence in the literature: advanced perception can provide strong chemical savings, but it is most useful when the underlying spray actuation is reliable.

Expected Contribution of the Review

The main contribution of this review is the integration of findings from 21 studies into a development-oriented framework for a solar-powered multifaceted agricultural sprayer. Instead of treating solar power, spraying mechanics, robotics and precision agriculture as unrelated topics, the review identifies how they can be layered. The basic machine can remain mechanically simple while still providing the interfaces needed for future automation. This approach is particularly relevant when the objective is an economical agricultural machine rather than a fully autonomous research platform.

The review also identifies a practical evaluation framework. Energy performance, hydraulic performance, field capacity, spray uniformity, operator safety, drift and operating cost should be measured together. This allows the final prototype to be compared with existing systems using engineering metrics rather than only descriptive claims. The resulting evidence can support later design optimization and a stronger experimental research paper after fabrication and field trials.

IX. RESEARCH GAPS

The 21 studies show that individual components of an advanced agricultural sprayer are well represented, but the literature is less consistent on the integration of renewable energy, spraying mechanics, mobility and precision control in one economical ground platform. This section converts the comparison into specific research gaps that can guide development and validation.

1. Solar–Battery–Pump Co-Design

Many studies demonstrate a particular PV and pump combination, but the proposed machine should be sized from a measured duty cycle. Pump power, required pressure, liquid discharge, drive load, operating time, battery depth of discharge and solar charging time should be considered together. This avoids oversizing the panel and battery while preventing insufficient energy during operation.

2. Application-Rate Calibration

A tank capacity or pump rating alone cannot demonstrate good spraying. The machine should be calibrated for discharge per nozzle, total flow, spray width, pressure and travel speed. Application rate should be reported in a form that can be compared between trials. The nozzle configuration should be selected for the crop and target rather than fixed solely for mechanical convenience.

3. Drift and Deposition Testing

The reviewed literature demonstrates that drift is influenced by droplet size, pressure, speed, nozzle design and environmental conditions [17], [19]. Future validation should therefore include water-sensitive paper or another suitable deposition method, droplet characterization where available, and tests under different operating conditions. A successful machine should minimize off-target deposition while maintaining target coverage.

4. Energy and Mobility Trade-Off

A solar panel, battery, tank, pump and chassis add mass. Larger tanks reduce refill frequency but increase traction and structural requirements. Larger batteries extend operation but increase weight and cost. A wider boom increases field capacity but can reduce maneuverability. The final design should therefore optimize the complete system rather than maximizing individual component ratings.

5. Remote Operation versus Cost

Remote control can reduce operator exposure, but motors, controllers, communication modules and additional batteries increase cost. The literature suggests that low-cost wireless control is feasible [1], [4], [13]. The proposed architecture should therefore support manual operation as the default and remote control as a modular upgrade.

6. Precision without Excessive Complexity

Machine vision and laser sensing can reduce chemical use, but their value depends on reliable detection and calibration [11], [18], [20]. For a first prototype, pressure regulation and interchangeable nozzles may provide a better cost-to-benefit ratio than immediate full autonomy. Sensor interfaces should nevertheless be provided so that precision features can be evaluated later.

7. Field Validation

The final machine should be tested across representative crops and field conditions. Measurements should include field capacity, application rate, nozzle uniformity, pressure stability, battery discharge, solar charging time, energy consumption per unit area, operator effort, drift or deposition behavior and operating cost. Repeated trials are necessary because a single demonstration cannot establish general performance.

Research Gap Statement

The central gap identified by the review is not the absence of solar sprayers, robots or precision systems individually. It is the limited integration of these functions into a simple, economical and mechanically robust ground platform that can be used by small and medium-scale farmers.

X. FUTURE SCOPE AND DEVELOPMENT PATHWAY

The literature supports a staged development strategy. Stage 1 should establish the mechanical frame, chemical tank, PV module, battery, pump, filter, pressure regulator and multi-nozzle boom. Stage 2 should quantify spray discharge, coverage, field capacity, battery performance and operator effort. Stage 3 can add remote vehicle control and safety interlocks. Stage 4 can add flow/pressure feedback, ultrasonic or laser sensing and GPS. Stage 5 can investigate machine vision and variable-rate spraying. This staged approach reduces development risk because each layer can be validated before the next is added.

The proposed machine should also be designed for maintenance. The tank should be removable, hoses should be accessible, filters should be easy to clean and nozzles should be replaceable. Electrical components should be protected from pesticide exposure and water ingress. The solar panel should be mechanically supported against vibration, while the battery should be securely restrained and electrically isolated during servicing.

For future precision operation, a camera-based system could detect crop rows or target regions and command individual nozzles or groups of nozzles. A flow sensor could verify that the commanded discharge is actually being delivered. Pressure feedback could compensate for changes in nozzle loading or battery voltage. GPS or RTK could provide repeatable row navigation. These functions are consistent with the direction demonstrated by the vision, UGV and variable-rate studies [11], [12], [18], [20].

The multi-purpose aspect can also be developed further. Pawar et al. identified the possibility of using solar agricultural equipment for tasks beyond pesticide spraying [8]. A sufficiently modular battery and controller could support auxiliary farm functions when the sprayer is not operating, improving utilization of the solar subsystem. Any such extension, however, should not compromise the primary requirements of safe chemical handling and reliable spraying.

XI. CONCLUSION

This review synthesized 21 research papers covering solar-powered sprayers, ergonomic knapsack systems, multi-nozzle application, remote and robotic vehicles, autonomous aerial spraying, air-assisted atomization, spray-drift management, variable-rate application and machine-vision precision control. The combined evidence shows that agricultural spraying is progressing from simple manual or fossil-fuel-powered operation toward renewable-energy and increasingly target-aware systems.

Solar-powered studies demonstrate that photovoltaic energy can operate electric pumps in both backpack and wheeled configurations, while dual-battery and switching arrangements can improve continuity [6], [7], [9], [21]. Multi-nozzle and air-assisted studies show that spray quality depends on nozzle type, pressure, distance, airflow and droplet characteristics [3], [14], [16]. Robotic studies demonstrate the safety and mobility benefits of remote operation [1], [4], [10], [13]. Precision studies provide evidence that crop-aware control can substantially reduce chemical use and drift under the tested conditions [11], [15], [18], [20].

Based on these findings, the proposed Development of Solar Powered Multifaceted Agricultural Pesticide Spraying Machine should be treated as a modular engineering platform. Its basic configuration should contain solar PV, charge control, battery storage, an efficient DC pump, pressure regulation, filtration, a replaceable multi-nozzle boom and a stable wheeled chassis. Remote control, flow/pressure feedback and crop sensing can be added progressively. The review does not claim experimental performance for the proposed machine; its role is to define a technically justified development direction from the existing literature.

The principal research opportunity is to validate this integrated architecture under Indian agricultural conditions and quantify its energy consumption, field capacity, application uniformity, operator effort, chemical use and operating cost. If these measures are demonstrated experimentally, the platform can provide a practical bridge between simple solar sprayers and more expensive precision-agriculture systems.

IX-A. DESIGN INTEGRATION MATRIX

The review findings can be converted into a direct design-decision matrix for the proposed machine. Renewable energy is the primary energy source, but battery storage is necessary because spraying demand does not always coincide with peak solar generation. The electric pump is the main hydraulic actuator and should be selected from the required nozzle flow and pressure. The multi-nozzle boom is the primary application mechanism and should be adjustable so that the same chassis can be adapted to different crops. The wheeled chassis provides mobility and carries the mass that would otherwise be imposed on the operator.

The control system should be layered. At the base level, the operator controls pump start/stop and vehicle movement. At the second level, pressure is regulated to the selected nozzle operating point. At the third level, feedback sensors can verify flow and pressure. At the fourth level, target sensing can decide where or when to spray. This layered structure is consistent with the literature because it allows the machine to remain useful even if advanced sensing is not available.

IX-B. RELATIONSHIP BETWEEN LITERATURE FINDINGS AND THE PROPOSED MACHINE

The solar-powered studies establish the feasibility of the energy subsystem, while the multi-nozzle study establishes the need for application calibration. The robotic studies establish that remote control can be used to reduce operator proximity. The precision studies establish that crop-aware control can reduce chemical use. The spray-drift studies establish that droplet and operating conditions must be considered when selecting pressure and nozzle type. No single study provides all of these functions simultaneously; the proposed machine therefore represents an integration of complementary findings rather than a direct duplication of one published design.

This distinction is important for the novelty of the proposed work. The review does not claim that solar-powered spraying, multi-nozzle spraying, remote operation or precision spraying is individually new. Instead, the engineering opportunity is to combine the most practical features into a low-complexity ground platform and then experimentally determine whether the combined design provides an acceptable balance between energy use, spray performance, mobility, safety and cost.

IX-C. PRACTICAL SELECTION OF THE INITIAL PROTOTYPE CONFIGURATION

For the first physical prototype, a wheeled chassis is preferable to a backpack because the principal purpose is to reduce the burden of carrying the tank and power system. A moderate-capacity chemical tank can be selected after the target crop and field size are defined. A DC diaphragm or comparable agricultural pump can be used with a pressure regulator and pressure gauge. The boom should use replaceable agricultural spray nozzles and a filter. The PV panel should be mounted above or behind the tank with adequate structural support and should not obstruct the operator's view.

A single battery configuration can be used for the first prototype if the duty cycle is short and charging can be performed between operations. A dual-battery arrangement similar to the system reported by Manab et al. can be considered if continuous operation is required [21]. Remote drive can be treated as an optional module. The minimum control system should nevertheless include an emergency stop and electrical isolation because the presence of a chemical tank and rotating or pressurized equipment creates safety requirements independent of automation.

The initial validation should use water instead of pesticide to establish hydraulic and mechanical performance. Once the spray pattern, leakage control, pressure stability and nozzle uniformity are verified, controlled agricultural trials can be performed using appropriate approved formulations and safe handling procedures. This sequence reduces development risk and allows mechanical problems to be corrected without exposing operators to chemicals.

IX-D. OVERALL REVIEW OUTCOME

The literature indicates that a successful multifaceted sprayer should not be defined by the number of advanced technologies it contains. A simpler machine with reliable pumping, uniform coverage, low operator burden and efficient solar charging can be more useful than a highly automated system that is expensive or difficult to maintain. The strongest future design is therefore a modular platform in which the core mechanical functions are robust and advanced functions are optional.

The final research opportunity is experimental validation. The proposed architecture provides a clear basis for fabrication, but the actual values of field capacity, energy consumption, spray uniformity, drift, operating cost and chemical savings cannot be claimed until measured. The review establishes the evidence-based design direction; subsequent prototype testing should establish the machine's own performance.

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